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# Accepted Manuscript

## Full Length Article

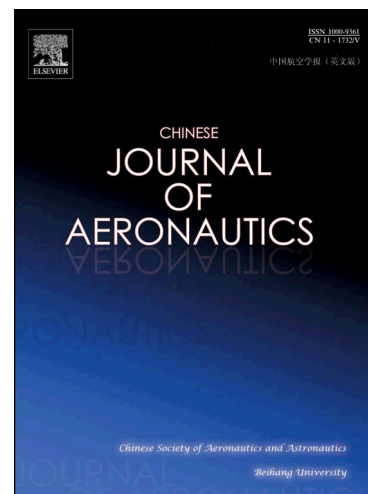
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# **An experimental study of the elastic properties of dragonfly-like flapping wings for use in Biomimetic Micro Air Vehicles (BMAV)**

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# **An experimental study of the elastic properties of dragonfly-like flapping wings for use in Biomimetic Micro Air Vehicles (BMAV)**

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## Abstract

This article studies the elastic properties of several Biomimetic Micro Air Vehicle (BMAV) wing structural designs that are based on a dragonfly wing. BMAVs are a new class of unmanned micro-sized air vehicles that mimic the flapping wing motion of flying biological organisms (e.g. insects, birds, or bats). Three structurally identical wings were fabricated using different materials: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and acrylic. Simplified wing frame structures were fabricated from these materials and then a nanocomposite film was adhered to them which mimics the membrane of an actual dragonfly. These wings were then attached to an electromagnetic actuator and passively flapped at frequencies of 10-250 Hz. A three dimensional high frame rate imaging system was used to capture the flapping motion of these wings at a resolution of 320 x 240 pixels and 35000 frames per second. The maximum bending angle, maximum wing tip deflection, maximum wing tip twist angle and wing tip twist speed of each wing were measured and compared to each other and an actual dragonfly wing. The results show that the ABS wing has considerable flexibility in the chordwise direction, whereas the PLA and acrylic wings show better conformity to an actual dragonfly wing in the spanwise direction. Past studies have shown that the aerodynamic performance of a BMAV flapping wing is enhanced if its chordwise flexibility is increased and its spanwise flexibility is reduced. Therefore, the ABS wing (fabricated using a 3D printer) showed the most promising results for future applications.

Keywords: Biomimetic Micro Air Vehicle; Acrylic; PLA; ABS; Flapping mechanism; Wing Structure

## 1.0 Introduction

Micro Air Vehicles (MAV) are a relatively new and rapidly growing area of aerospace research. They were first defined by the US Defense Advanced Research Projects Agency (DARPA) in 1997 as unmanned aircraft that are less than 15 cm in any dimension. Later in 2005, DARPA defined aircraft with all dimensions less than 7.5 cm and lighter than 10 g (carrying 2 g payload) as Nano Air Vehicles (NAV). MAV (or NAV) generally fit into three categories: fixed wing, rotorcraft, or biomimetic. Biomimetic MAV (BMAV) mimic the flapping wing motion of flying organisms (e.g. insects, birds, bats, etc.). This allows lift and thrust to be achieved from a relatively small wing surface area. This allows BMAV to potentially be smaller and more

lightweight than the other two types. These characteristics make BMAV ideally suited for flight missions in confined areas (e.g. around power lines, narrow streets, indoors, etc.). Therefore, BMAV structural components must be ultra-lightweight, compact, and flexible. Most past MAV research has focused on fixed wings, which are essentially scaled-down versions of wings on conventional fixed wing aircraft. These wings are unsuitable for BMAV due to their lack of flexibility. So a new type of structural wing design is required for BMAV. In this work, a dragonfly wing structure is mimicked to construct a new BMAV wing design. A dragonfly (*Odonata*) was selected for biomimicry, because they are highly maneuverable flyers, capable of hovering, rapid forward flight, or reverse flight. Therefore, structurally analyzing these wings could yield results that bioinspire the design of more effective wings for BMAVs. This article follows on from research discussed in a previous article (written by the authors) that analyzed the static strength of dragonfly-like wing frames fabricated from common materials used in unmanned aircraft (balsa wood, black graphite carbon fiber and red pre-impregnated fiberglass).<sup>1</sup>

Several past research publications have been conducted on flying insect wing structures to understand their elastic properties. Herbert et al.<sup>2</sup> conducted numerical investigations on a tethered desert locust (*Schistocerca gregaria*). They concluded that the wings must undergo an appropriate elastic wing deformation (through the course of a wing beat) in order to achieve an efficient aerodynamic flow suitable for lift and thrust generation. Several studies showed that flexible wings, capable of changing their camber, generate higher peak lift forces than rigid wings.<sup>2-3</sup> Wing flexibility also prevents small tears or warping from occurring. Young et al.<sup>4</sup> suggested that dragonfly wings appear to be adapted for reversible failure in response to excess loads, enabling them to avoid permanent structural damage. Jianyang et al.<sup>5</sup> conducted a study on the effect of flexibility on flapping wing performance during forward flight. A two-dimensional numerical simulation was done by solving the unsteady incompressible Navier–Stokes equations, coupled with the structural dynamic equation for the motion of a wing. The results show that the flexibility of a flapping wing can largely influence its aerodynamic characteristics. If the wing has an appropriate flexibility ( $0.67 \leq \omega^* \leq 0.91$ ), the flexibility can simultaneously increase both the propulsive and lifting efficiencies of the wing. Kei Senda et al.<sup>7</sup> conducted a study in which deformation of the wings is modeled to examine the effects of

bending and torsion on the aerodynamic forces. Their numerical simulations demonstrated that flexible torsion reduces flight instability. They concluded that the living butterflies have structurally flexible wings that improve both the aerodynamic efficiency and flight stability. Their experimental measurements showed that a uniformly flexible wing generates lower aerodynamic forces than rigid wings under steady-state conditions. However, the presence of wing veins can substantially enhance aerodynamic performance to match or improve the rigid airfoil. These observations agree with Zhao et al.<sup>8</sup> who concluded that flexible, insect wings generate greater forces due to an enhanced camber in flight.

Luo et al.<sup>9</sup> and Fang et al.<sup>10</sup> found that chordwise deformation of an elastic wing is greater during upstroke than during downstroke. In a study conducted by Ngoc et al.<sup>11</sup> the asymmetric bending of a *Allomyrina dichotoma* beetle's hind wing was investigated. Five differently cambered wings were modeled using the ANSYS finite element analysis software. These models were subjected to loads and pressures from the dorsal side and ventral sides. The results revealed that both the stressed stiffening of the membrane and the wing camber affect the bending asymmetry of insect wings. In particular, increasing the chordwise camber increased the rigidity of the wing when load was applied on the ventral side. Alternatively, increasing the spanwise camber increased the rigidity of the wing when the load was applied on the dorsal side. These results explain the bending asymmetry behavior of the flapping insect wings. Yang et al.<sup>12</sup> conducted research on the effects of chordwise and spanwise flexibility on the aerodynamic performance of micro-sized flapping wings. Four flapping motions were described: pure rigid flapping (no deformation), pure spanwise flapping, pure chordwise flapping, and combined chord-spanwise flapping motions. Their results show that a large spanwise deflection reduces the aerodynamic performance (e.g. lift and thrust generation) and a large chordwise deflection increases the performance. They further suggest that the design of a flexible flapping wing should incorporate characteristics that will create a suitable chordwise deformation angle ( $25^\circ$  and above) and limit the spanwise deformation angle ( $5^\circ$  and less).

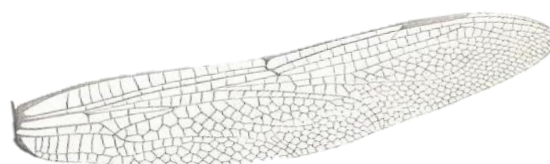
Mountcastle et al.<sup>13</sup> conducted an experiment using artificially stiffened bumblebee wings (in vivo) by applying a micro-splint to a single flexible vein joint. The bees were then subjected to load-lifting tests. Bees with stiffened wings showed an 8.6 per cent maximum lift reduction. This reduction cannot be accounted for by changes in gross wing kinematics,

since the stroke amplitude and flapping frequency were unchanged. The results reveal that flexible wing design and the resulting passive wing deformations enhance the load-lifting capacity in bumblebees. Wu et al.<sup>14</sup> presented a multidisciplinary experiment that correlated a flapping wing's elasticity and thrust production, by quantifying and comparing overall thrust, structural deformation and airflow. Six pairs of hummingbird-shaped membrane wings of different properties were examined. The results showed that, for a specific spatial distribution of flexibility, there is an effective frequency range in thrust production. The wing deformation at thrust-producing wing-beat frequencies indicated the importance of flexibility. Both bending and twisting motion interact with aerodynamic loads to enhance wing performance.

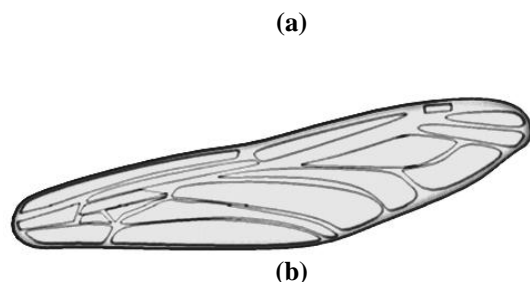
Most past research, that are similar to the objectives of this article, examined the effects of wing flexibility on aerodynamic performance by either using numerical models or experimentation. However, very few researchers have attempted to mimic the detailed structure of an actual insect wing. In this article, biomimicry of a dragonfly wing (frame structure and membrane) is done by fabricating them with different materials: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and acrylic. The focus of this article is solely on the flexibility of the fabricated wing structures and not the resulting aerodynamic forces that are generated. The wings were fixed to a flapping mechanism and flapped at variable wing beat frequencies. An actual dragonfly has a natural frequency of 120-170 Hz and a wing beat frequency of 30 Hz. The mechanism used in this study was able to flap up to a maximum wing beat frequency of 250 Hz. This allowed us to study the deformation of wing motions at frequencies beyond the ability of an actual dragonfly. The resulting wing tip deflection, twisting angles, twisting speed and bending angles were measured using imagery generated by two high frame rate cameras. Comparisons are made with a real dragonfly wing in passive flapping motion.

## 2.0 Materials and Methodology

### 2.1 Wing Design and Fabrication







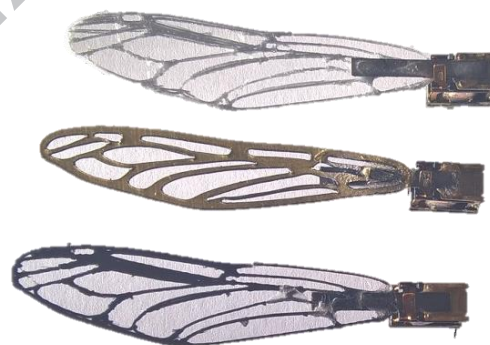
**Fig. 1** Dragonfly wing structure comparison; (a) actual wing and (b) simplified wing.

Figure 1 shows the comparison of an actual dragonfly wing (*Diplacodes Bipunctata*) to the simplified wing frame structure used in this study. The simplified frame structure is designed based on spatial network analysis, which is described in a past article written by the authors<sup>15</sup>. This analysis utilizes geometric objects within a region specified by vertices or edges. Although this method is commonly used in Geographical Information Systems (GIS) to explore geographic spatial patterns, the idea of applying this algorithm to a biological structure was first introduced in this article. It was inspired by observing the compactly arranged geometrical patterns inherent to dragonfly wings. The method allows this complex biological structure to be mimicked by a simplified frame structure that can be fabricated by machining or 3D printing.

All of the simplified frame structures were fabricated to be approximately 55 mm in length and 0.05 mm thick. As previously mentioned, they were constructed of three different materials: acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and acrylic (Figure 2). The ABS and PLA wings were fabricated using a Maker Bot Replicator 2X 3D printer. The acrylic wings were fabricated using micro laser machining. Acrylic or polyacrylate are generally known for their resistance to breakage, elasticity and flexibility<sup>16-17</sup>. ABS and PLA are the two most dominant plastics used for 3D printing. ABS is chosen due to its strength, flexibility, and machinability<sup>11</sup> while PLA is chosen for its biodegradability, lightweight, flexibility and elasticity<sup>18</sup>. The densities of ABS, PLA, and acrylic are 1.05 and 1.19, and 1.18 g/cm<sup>3</sup>, respectively. A finite element analysis on von Mises stress were conducted to simulate the flexibility of the materials tested.

A chitosan nanocomposite film was bonded to the wing frames to serve as a thin (3 mm), ultra-

lightweight wing membrane. This chitosan nanocomposite film was developed by our research team for this specific purpose and is the subject of another article<sup>19</sup>. It has similar properties to the chitin membranes of real dragonflies. It is formed by reinforcing a chitosan suspension with nanometer-scaled nanocrystalline cellulose (NCC) particles and tannic acid. This allows both the mechanical properties and water resistivity of chitosan film to be controlled to achieve suitable design values. The use of NCC as a filler material elevates the film's mechanical properties (e.g. rigidity). The addition of tannic acid as a cross-linking agent reduces the swelling behavior, solubility and the rigidity of the nanocomposite film. The film was adhered to the wing frame by first submerging the frame into the nanocomposite solution. This procedure also ensured that the film membrane would have a prescribed, uniform thickness and that both sides of the frame structure were evenly coated. The suspension was then transformed into a film by the casting evaporation method. Once cured, the film created a shiny, transparent film layer that adhered firmly to the frame structure.



**Fig. 2** Wing frame materials of PLA, acrylic and ABS respectively.

**Table 1** Mechanical properties of frame structure materials<sup>16,18</sup>

Material	Density (kg/m <sup>3</sup> )	Modulus of Elasticity (N/m <sup>2</sup> )	Poisson Ratio
Polylactic acid (PLA)	1190.0	3.50x10 <sup>9</sup>	0.36

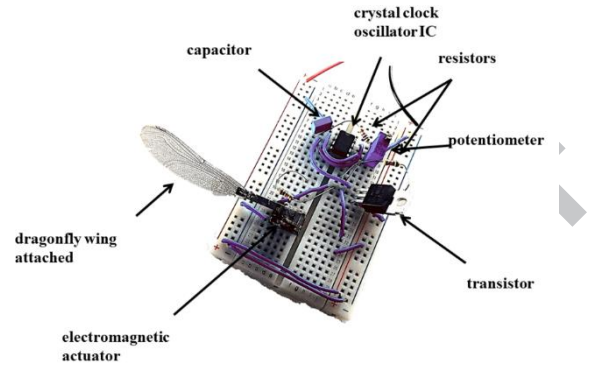
Acrylic	1180.0	$3.32 \times 10^9$	0.35
ABS	1050.0	$2.80 \times 10^9$	0.35

Material	Shear Modulus of Elasticity ( $\text{N/m}^2$ )	Thickness (m)
Polylactic acid (PLA)	$3.37 \times 10^9$	$2 \times 10^{-4}$
Acrylic	$6.20 \times 10^7$	$2 \times 10^{-4}$
ABS	$1.03 \times 10^9$	$2 \times 10^{-4}$

## 2.2 Wing Flapping Mechanism

The wing flapping mechanism used in this study is an electromagnetic flapping wing actuator. The power supply used in this flapping wing drive is 9 volts DC. A LM555 crystal clock oscillator integrated circuit (shown in Figure 3) is used to generate a stable oscillation. The free running frequency and duty cycle are accurately controlled with two resistors and one capacitor. The generated oscillation is fed to a Power MOSFET fast switch. The output of the Power MOSFET is used to actuate the miniature PC Board Relay. The frequency of the switch (corresponding to the wing beat frequency) can be adjusted by a 22 k $\Omega$  potentiometer. Each of the different wings is attached to a flat iron plate (2 mm long and 2.75 mm thick) using super glue. This plate (wing platform) is oscillated by an electromagnetic actuator (3 x 3 mm). Figure 3 shows the wing structures attached to the actuator. The plates are attached to the hinge of the wing to mimic the joint of an actual dragonfly. This flapping mechanism is able to create a linear up-down stroke motion at variable wing beat frequencies, up to a maximum frequency of 250 Hz. The flapping degree was set to be 60° which corresponds with an actual dragonfly wing flapping angle during hovering flight.

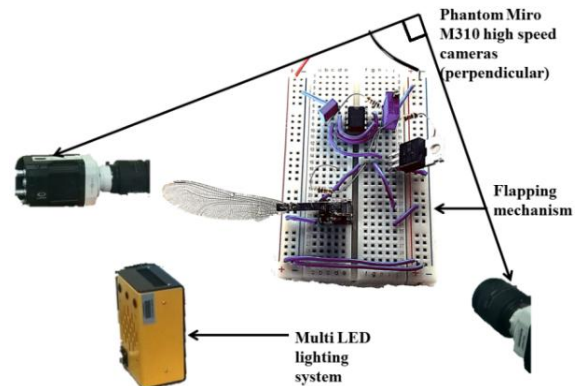
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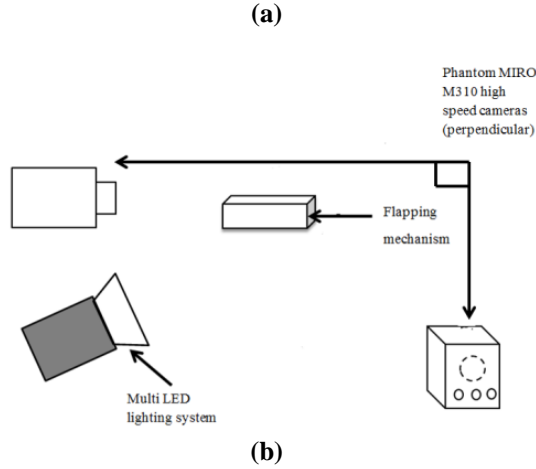
**Fig. 3** Flapping mechanism used in this study.

## 2.3 Experimental Set-up

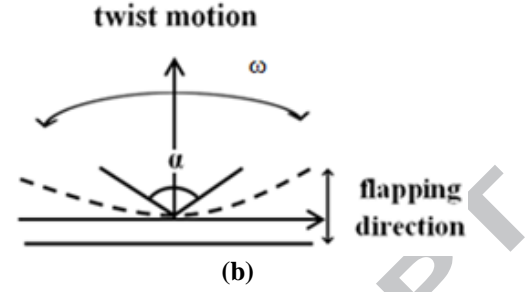
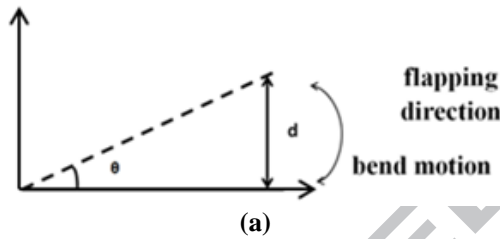
Two Phantom Miro310 (Vision Research) high frame rate cameras were used to view the flapping wings from two different directions. The camera's high frame rate enables a precise sequence of images to be captured of the flapping wing motion within a single wing beat. Two cameras were necessary in order to determine the three-dimensional shape and orientation of the wing surface (Figure 4). The cameras were placed perpendicular to one another following the procedures established by Gui et al.<sup>21</sup> Both cameras were equipped with a Nikon F lens. A multiple LED lighting system was used to provide sufficient illumination. Imagery was recorded at a resolution of 320 x 240 pixels and a frame rate of 35000 per second, which allowed the wing beat motion to be precisely captured. The motion video was stored to a computer via two high speed Ethernet cables. It was played-back and analyzed using the Vision Research Phantom Camera Control Software (version 2.6.749.0).







**Fig. 4** Experimental set-up: Two high-speed cameras perpendicular with multi LED lighting.



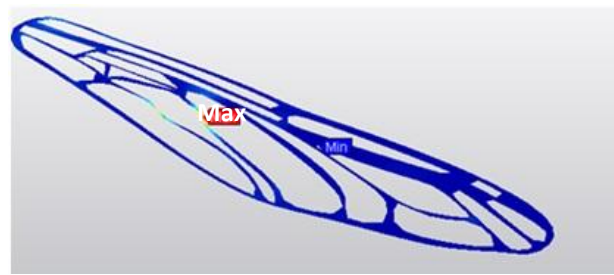
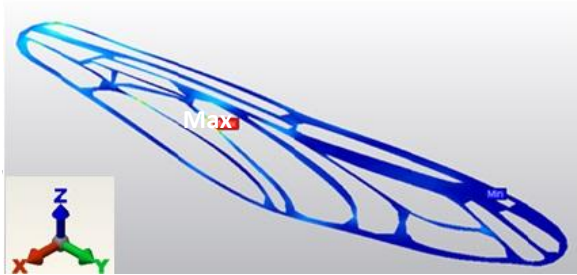
**Fig. 5** (a) Front view and (b) side view of the wing motion captured (and measurement axes).

Measurements were taken of each of the three wings while flapping at varying frequencies: 10 - 250 Hz. Figure 5 shows the front and side view of the wing motions that were measured and recorded from captured imagery. Figure 5a illustrates the bending angle ( $\theta$ ) and displaced distance or deflection ( $d$ ). Figure 5b defines the wing tip angle ( $\alpha$ ) and the wing tip rotational twist speed ( $\omega$ ).

### 3.0 Results and Discussion

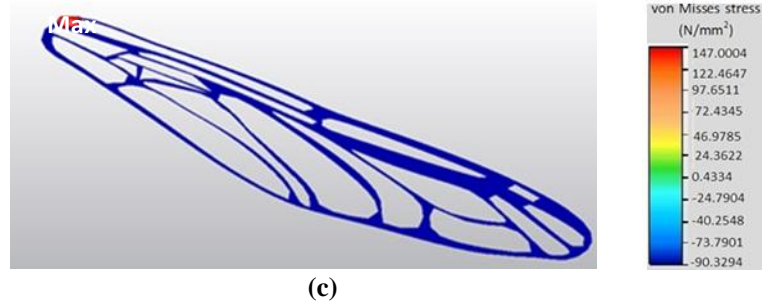
#### 3.1 Stress Simulation Results (without membrane)

A stress simulation analysis was done on the wing frame materials (without and with membrane) tested in this experiment using Autodesk Simulation Multiphysics 2015. These results directly relate to the flexibility of the materials tested in this experiment. The results are shown in Figures 6 and 7.



(a)

(b)

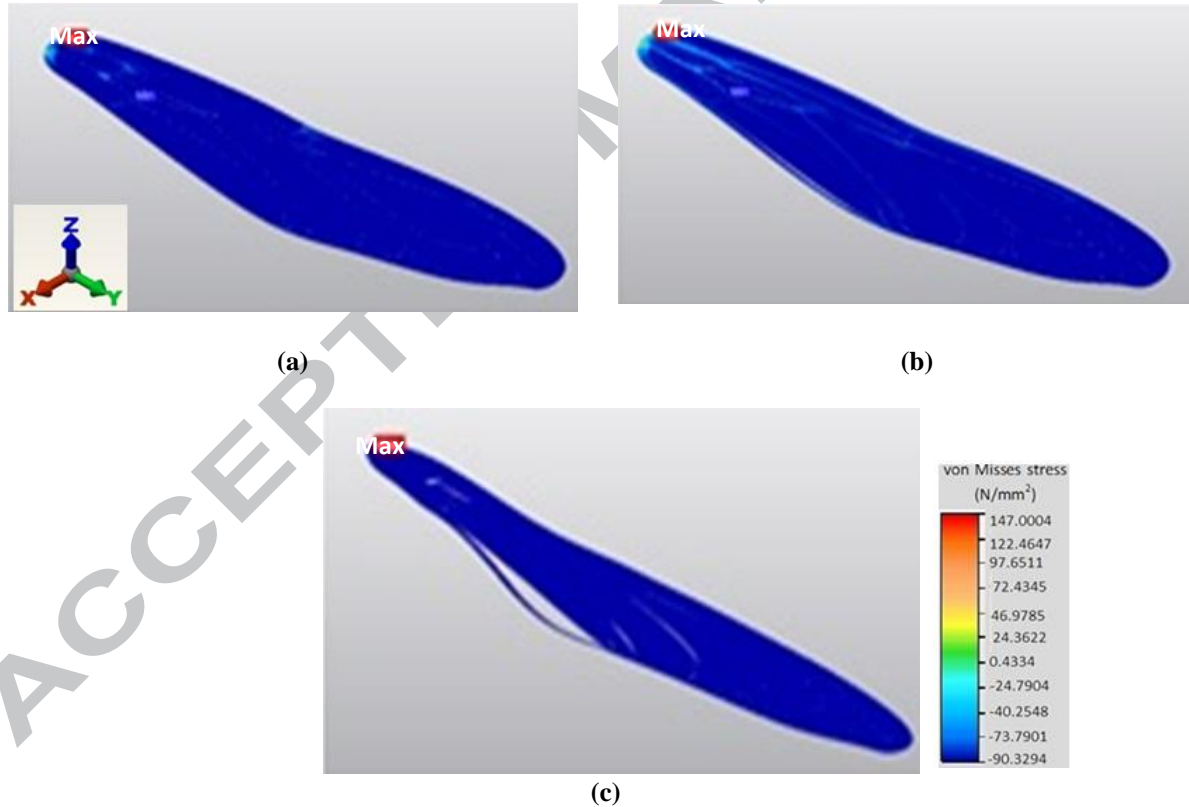


**Fig. 6** Stress simulation results for a) ABS; b) PLA; and c) acrylic (without membrane)

Figure 6 shows the von Mises stress results of all the three different frame structures. The highest stress in the forewing recorded for PLA, acrylic and ABS is: 13 N/mm<sup>2</sup>, 17 N/mm<sup>2</sup>, and 23 N/mm<sup>2</sup>

respectively. This shows that ABS is the least flexible material among all three materials tested without a membrane.

### 3.2 Stress Simulation Results (with membrane)



**Fig. 7** Stress simulation results for a) ABS; b) PLA; and c) acrylic (with membrane)

Figure 7 shows the forewing models of all three materials used in this experiment. Based on Figure 6, the maximum von Mises stress occurs at

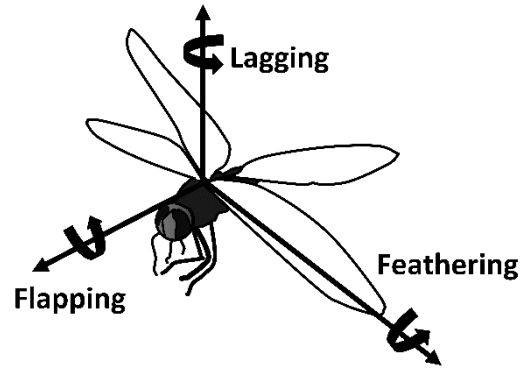
approximately the same location for all three materials. The highest stresses occur in regions where the surface-to-area ratio is minimum. The maximum

stress recorded is: 14.77 N/mm<sup>2</sup>, 17.29 N/mm<sup>2</sup>, and 24.23 N/mm<sup>2</sup> for PLA, acrylic and ABS, respectively. Both Figures 6 and 7 show that ABS exhibits the maximum stress among all three materials.

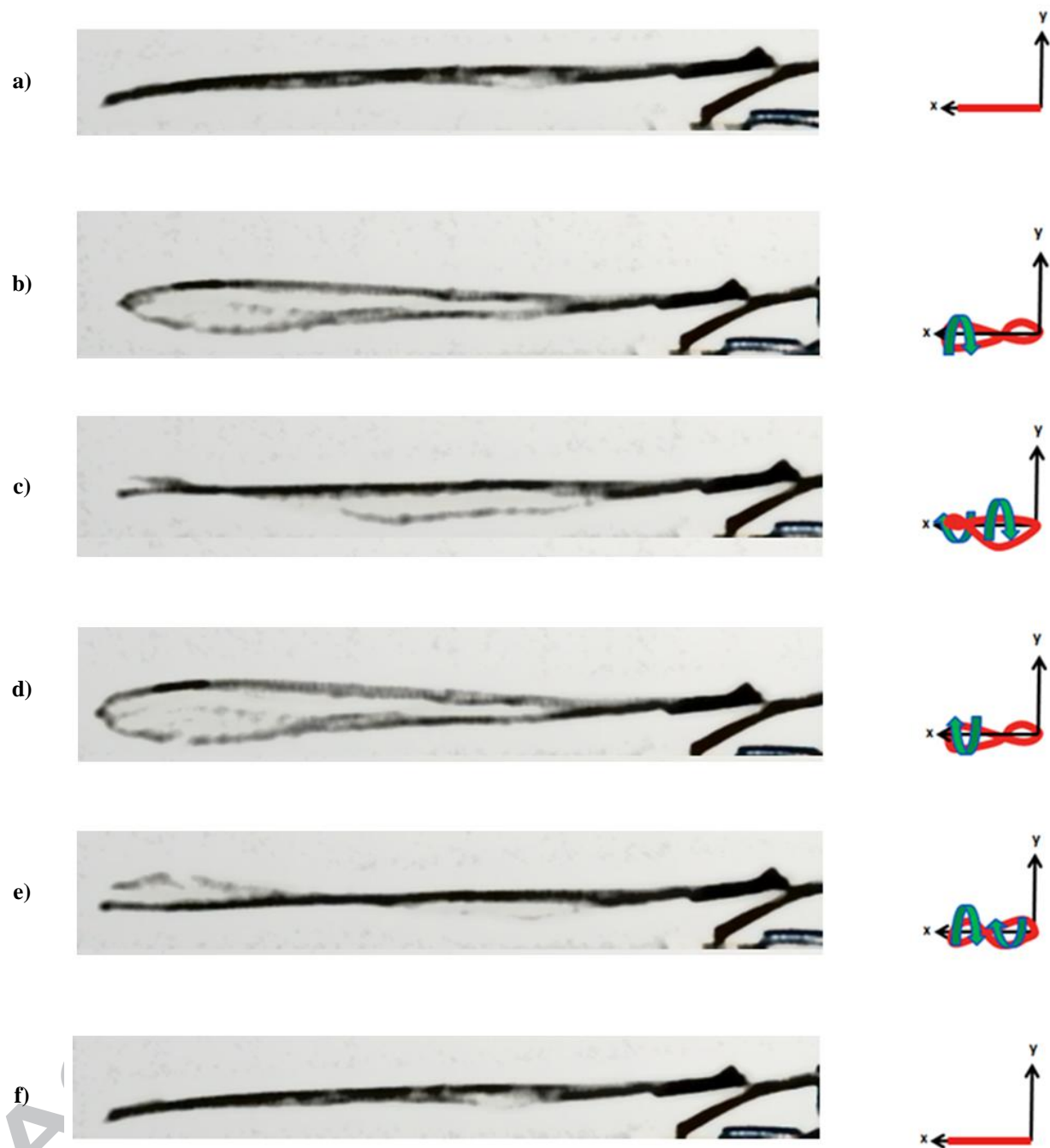
### 3.3 Dragonfly Wing Flapping Motion

The experiment was conducted on each of the three types of wings (both with and without the chitosan membranes). This was done to study the flexibility of each wing frame material and to determine the best material for use in a BMAV. An actual dragonfly wing (*Diplacodes Bipunctata*) was also tested to study its motion during passive flapping at different frequencies and compare it with the fabricated wings. The nomenclature for wing rotation about different axis is shown in Figure 8. Figures 9 and 10 shows a sequence of images, illustrating the wing motion of an actual flapping dragonfly wing during one complete flapping cycle. The wing beat frequency for

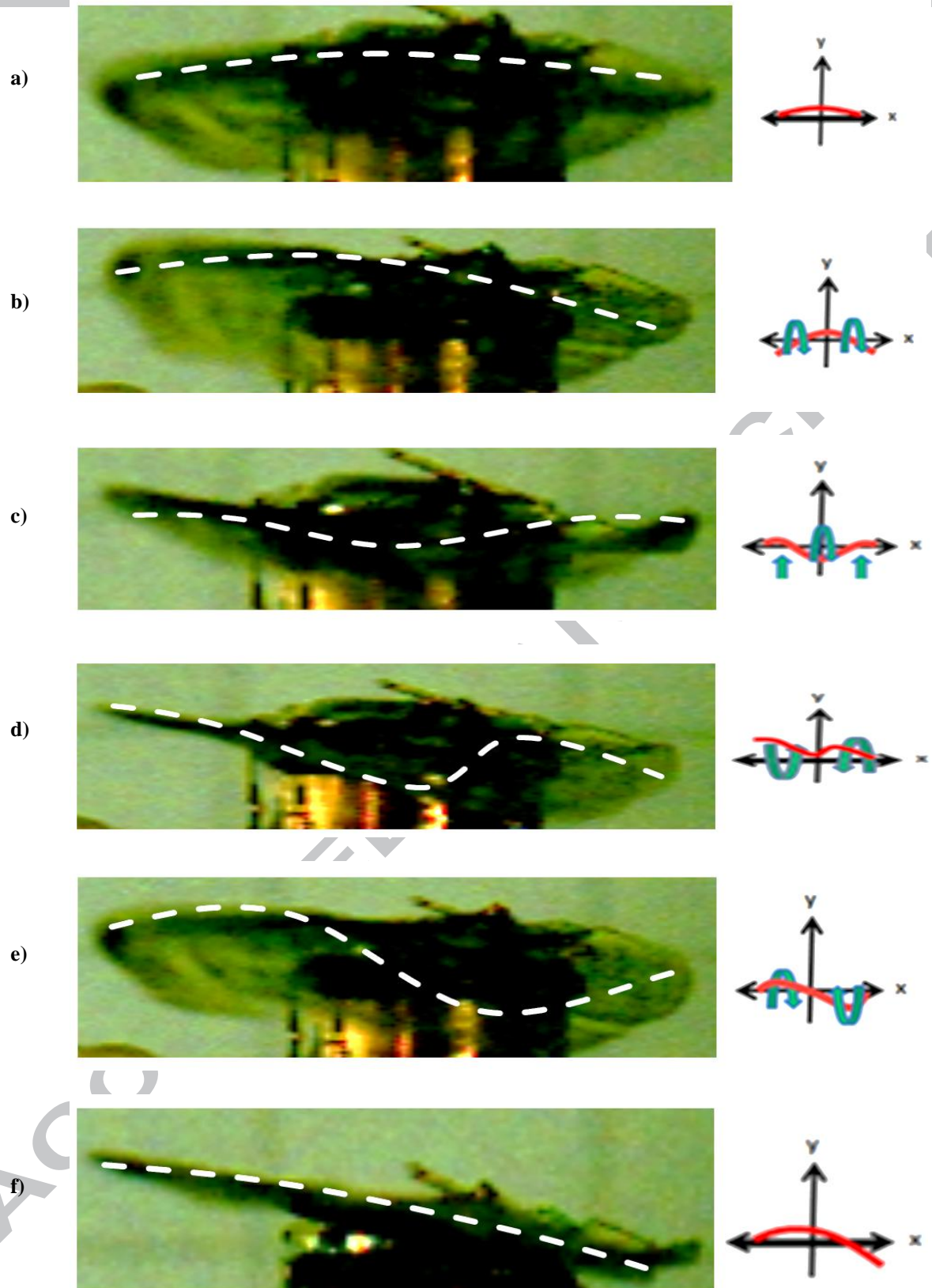
these images is 30 Hz, which is the nominal wing beat frequency of this species of dragonfly.



**Fig. 8** Degrees of freedom for the wings of flying insects<sup>22</sup>



**Fig. 9** Side view of the dragonfly flapping wing (gray scale) captured by the high speed camera during one flapping cycle at 30Hz. a) Start of downstroke; b) mid-downstroke; c) end of downstroke; d) start of upstroke; e) mid-upstroke; f) end of upstroke



**Fig. 10** Front view of the dragonfly flapping wing captured by the high speed camera (gray scale) during one flapping cycle at 30 Hz. a) Start of downstroke; b) mid-downstroke; c) end of downstroke; d) start of upstroke; e) mid-upstroke; f) end of upstroke



Dragonfly wings greatly deform during flight. This was observed in our experiment as well as others<sup>23</sup>. Despite having a certain degree of rigidity, dragonfly wings undergo a considerable amount of bending, twisting and rotational motions. Figures 9 and 10 shows the motion of flapping wing in one complete cycle at 30 Hz (side and front view). It was observed that at both directions (chord and spanwise) an asymmetric twist-bend motion was observed. Figures 9d, 9f, and 10d clearly show these asymmetric motions mentioned. At the end of an upstroke (observed in Figure 8e), the wing momentarily exhibited a symmetrical twisting motion. A large feathering rotation range of  $154^\circ$  to  $179^\circ$  of the entire wing was observed during the beginning of the down stroke and end of the upstroke (for all frequencies) (Figure 10a and 10e). Even during the steady phase (passive moment occurring when the flapping angle is zero), the wing is observed to undergo internal torsion. This corresponds well to previous studies made by Wootton et al.<sup>2,24</sup>

Besides the nominal 30 Hz wing beat frequency, the dragonfly wing was also flapped at frequencies ranging from 10 - 250 Hz. The pattern of deformations was similar for all of the frequencies observed. The measured bending angle, wing tip deflection, wing tip twist angle and speed for the different wing frames (without and with a membrane) were plotted in comparison to the results obtained from an actual dragonfly wing in Figures 11-14.

### 3.4 Bending Angle versus Flapping Frequency

The bending angle is directly proportional to the flexibility of the wing. Both inertial and aerodynamic loads influence it. Wootton<sup>24</sup> found that most insect wings have relatively stiff supporting zones near the wing base and leading edge. Adding to this in a later article, Wootton<sup>25</sup> wrote that the wing veins taper in diameter from base to tip. The resulting reduction in stiffness reduces the inertial load at the wing tips, reducing the energy expenditure and stress at the wing base. Ennos and Wootton<sup>26</sup> showed that wings that have a tapered stiffness distribution from base (high) to tip (low) are well suited to withstand torques. This article also showed that spanwise bending moments due to the inertia of the flapping wings is approximately two times larger than those due to aerodynamic forces. A structural finite element analysis by Jongerius et al.<sup>27</sup> of a dragonfly wing model, also showed that the inertial forces along the wingspan are 1.5 to 3 times higher than the aerodynamic forces. Similarly, Combes and Daniel<sup>28</sup>

modeled a dragonfly and hawkmoth wing and found that the flexural stiffness declined exponentially from wing base to tip. Although inertial loading dominates, Young et al.<sup>4</sup> showed that aerodynamic forces (e.g. lift and thrust) generated by the flapping wing also has an influence on wing flexibility.

This study focuses only on the chordwise flexibility of a passive flapping wing. Bending angles were measured along the chordwise direction. Chang et al.<sup>23</sup> also investigated chordwise flexibility, but for simple, non-anisotropic wing structures. They presented a detailed assessment of the effects of structural flexibility on the aerodynamic performance of flapping wings. The Reynolds number ( $Re = 100$ ) considered in this study is relevant to small insect flyers, such as fruit flies. However, this study only includes the role of chordwise flexibility and passive pitch in two dimensional plunging motions.

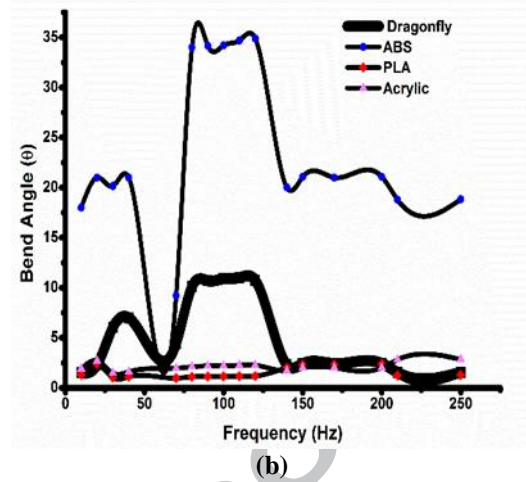
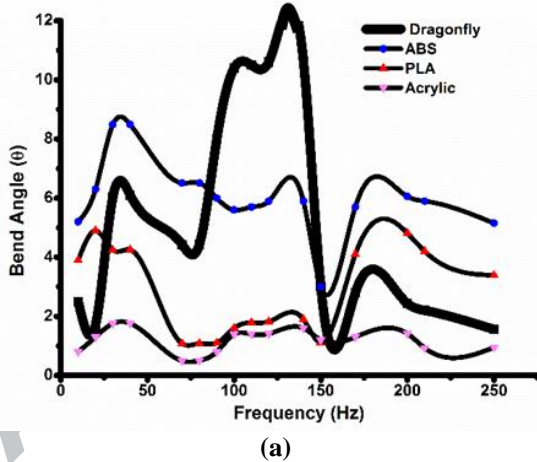
Our study involves a much more complex wing design than in many past studies. However, tapering the thickness (declination from base to tip) of the veins in our physical models (similar to actual insect wings) was not possible due to fabrication limitations. Our wings have tapered flexibility (declining from base to tip and from leading to trailing edge) solely due to a reduction in the frame planform width sizes (mimicking veins) in these directions. Figure 11 shows the bending angles as the wing beat frequency is varied for the three fabricated wing frames (without and with a membrane) in comparison to an actual dragonfly wing. These figures show that the maximum bending angle ( $\theta_{max}$ ) for all the wings occurs during the upstroke. This was observed for both frames (without and with a membrane). This agrees with previous research done by Jongerius et al.<sup>27</sup>, in which this asymmetry (difference in bending angle between the upstroke and down stroke) was attributed to the directional bending stiffness in the wing structure (e.g. one-way hinge or a pre-existing camber in the wing surface).

The maximum bending angle of dragonfly wings at 30 Hz is recorded to be about  $6^\circ$ . The wings were observed to have a maximum bending angle of  $10.7^\circ$  at 120 Hz (natural frequency of an actual dragonfly). This is an increase of 78.3% from 30 Hz. ABS shows a high level of flexibility compared to the other two materials used. Figure 11 shows that the bending angle curves of the fabricated ABS wings are more similar to the actual dragonfly wing than the other two types. Figure 10a shows that the bending angle of ABS wing (without membrane) at 30 Hz is  $8.5^\circ$  and  $5.9^\circ$  at 120 Hz. At 30 Hz, the percentage difference between an ABS wing (without



membrane) and an actual dragonfly wing is about 41.7%. The PLA and acrylic wings each recording a percentage difference (reduction) of 70%. In Figure 11b, ABS exhibits much larger bending angles at 30 Hz when the membrane is added. The value of the ABS wing (with membrane) is  $20.1^\circ$  at 30 Hz and  $34.9^\circ$  at 120 Hz. This angle is much larger than the actual dragonfly wing. The percentage increase between the ABS and an actual dragonfly wing is 233.3%. The other two materials (PLA and acrylic) exhibited much lower bending angles than the actual dragonfly wing. The percentage reduction in PLA and acrylic (in comparison to an actual dragonfly wing) is 83.3% and 75%, respectively.

These observations confirm that the overall flexibility of the wing decreases after the membrane is attached, except for ABS. At a frequency of 120 to 170 Hz, the dragonfly wing bends at a very high angle. Previous research shows that dragonflies do not flap at their natural frequency (120 to 170 Hz).<sup>29</sup> So this result is likely due to a resonance effect caused by the wing beat frequency being proximate to the natural frequency of the wing. This result confirms that dragonflies have a maximum wing beat frequency limitation in this range. The ABS wing frame shows a similar trend at 120 Hz. The bending angle is reduced at frequencies greater than 120 Hz for both the actual dragonfly wing and the three fabricated wings.



**Fig. 11** Bending angle of different wing frames; (a) without membrane and (b) with membrane.

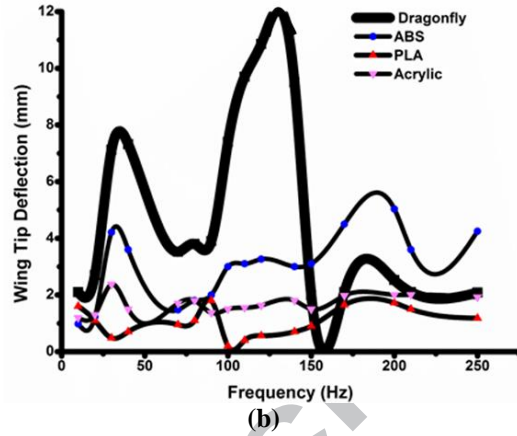
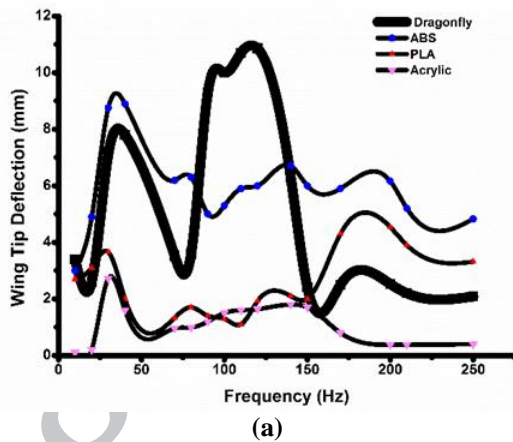
### 3.5 Wing Tip Deflection versus Flapping Frequency

Figures 12a and b show the wing tip deflection for varying wing beat frequencies of the three fabricated wing frames (without and with membranes) in comparison to an actual dragonfly wing. Similar to bending angle, deflection is another measurement that can be used to assess a flapping wing's flexibility. As mentioned earlier, past studies have shown that wing flexibility has a significant effect on the wing's ability to generate a suitable time-averaged lift or thrust<sup>8</sup>. Similar to  $\theta_{max}$  in Figure 10, Figure 12 shows that the maximum deflection ( $d_{max}$ ) occurs during the upstroke. This again was observed for both frames (without and with a membrane). This agrees with previous research done by Luo et al.<sup>9</sup>

Figure 12a shows that all of the fabricated wing frames (without membrane) deflect at magnitudes that are similar (only slightly reduced) to the actual dragonfly wing at 30 Hz which is about 7.1 mm. At 30 Hz, ABS has a percentage increase of 23.94%. PLA and acrylic both have a percentage reduction of 47.71% and 62% respectively. However Figure 12b, shows that the fabricated wing frames (with membranes) have very different deflections than the actual dragonfly wing. Only the ABS wing showed a comparable level of deflection, however the dragonfly wing is 40.85% lower than the ABS wing. The PLA and acrylic wings have percentage reduction of 94.37% and 66.2%, respectively compared to the dragonfly wing. The actual dragonfly wing is able to undergo a large deflection at the tip region. This supports previous studies

which explain that the difference between the deflection at the tip and the surface is created by differences of the rigidity (due to the vein and corrugations) along the wing surfaces<sup>30</sup>.

The difference in deflection between wing frames without a membrane and with a membrane shows that the attachment of a membrane causes an increase in rigidity. This increase in rigidity is observed to be the highest in the PLA wing. Only the ABS wing shows a similar curvature trend with the actual dragonfly wing around 120 Hz. At 120 Hz, an increase in percentage of 81.7% (without membrane) and decrease in percentage of 69.7% (with membrane) is seen in ABS wing frame. Compared to the PLA wing there is a percentage reduction of 82.6% (without membrane) and 64.2% (with membrane). The acrylic wing has a percentage reduction of 85.3%, both without and with the membrane attached. The trend of the graph again shows that there is a decrease in flexibility after the membrane has been attached. Two high peaks were observed for an actual dragonfly wing (30 and 120 Hz). As already stated, the natural frequency of dragonfly wings has been reported to be between 120 to 170 Hz.<sup>29</sup> The extreme fluctuation observed in this range confirms the reporting.



**Fig. 12** Wing tip deflection of different wing frames; (a) without membrane and (b) with membrane.

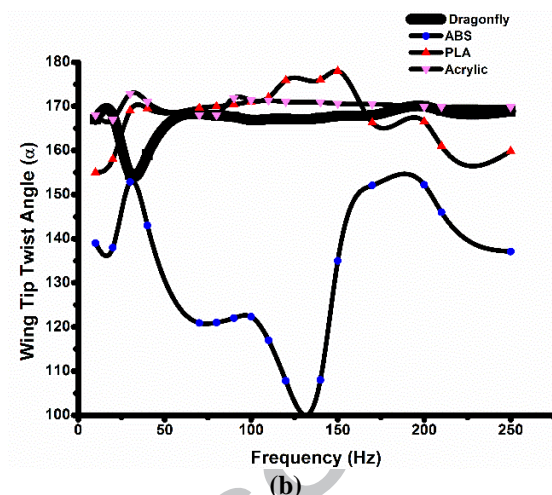
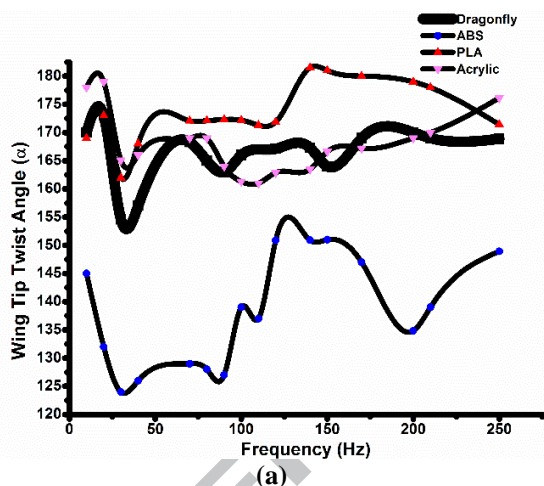
### 3.6 Wing Twist Angle versus Flapping Frequency

Figure 13 shows the maximum wing tip twist angle of the three fabricated wing frames in comparison to an actual dragonfly wing. The maximum twist angle was recorded during the stroke reversal (transition from upstroke to down stroke). The twist angle for an actual dragonfly wing at 30 Hz is 154.58°. Untwisted wings have large, drag producing wing surfaces that are exposed to flow hence the importance of twisting in wings are justified. Wing tip twist also plays an important role in enhancement of flight performance. The mid-stroke timing of wing deformation in the butterfly, examined by Lingxiao et al.<sup>30</sup>, suggests that the deformation is not due to wing inertia, because the acceleration of the wing is small at this point in the stroke. They suggest that this is instead due to elastic effects, since the aerodynamic forces are very large at mid-stroke.

Figures 13a and b show that both the PLA and acrylic wing frames (both without and with membranes) closely match the performance of an actual dragonfly wing. At 30 Hz, the ABS (without and with membrane) has a percentage reduction of 19.8% and 1.10% respectively in comparison to the actual dragonfly wing. The PLA wing (without and with membrane) has a percentage increase of 5.2% and 9.7% respectively. The acrylic wing (without and with membrane) has a percentage increase of 7.1% and 11.7% respectively. At 120 Hz, the ABS and acrylic wings (without membrane) has a percentage reduction of 10.2% and 2.5%, respectively compared to the dragonfly wing. While the PLA wing (without

membrane) has a percentage increase of 2.9%. The ABS wing (with membrane) has a percentage reduction of 35.9% compared to the dragonfly wing. While the PLA and acrylic wings have a percentage increase of 5.3% and 3.6% respectively. Based on these results, the PLA and acrylic wings are more similar to the actual dragonfly wing than the ABS wing. The large fluctuation of the ABS wing across varying flapping frequencies (10 to 250 Hz) makes it a more complicated BMAV option.

Another trend observed from Figure 13 is that the wing tip twist angle of the dragonfly wing does not vary significantly as the flapping frequency is varied. This matches a previous study by Zhao et al.<sup>8</sup> (mentioned earlier) which shows that the flexibility of insect wings increases more chordwise than spanwise, due to the rigid leading edge vein. This is true for both categories of wing frames (with and without membrane).



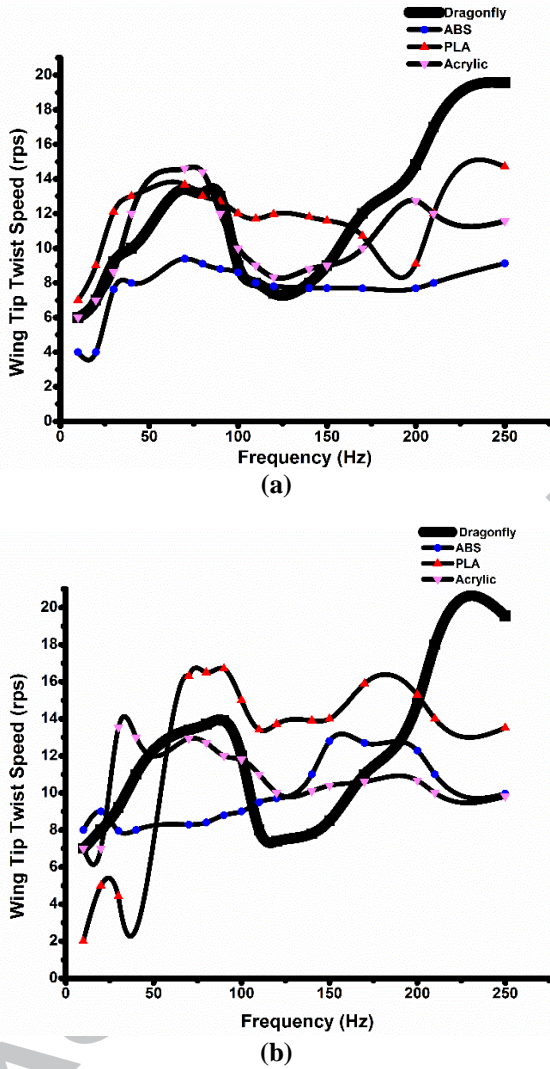
**Fig. 13** Wing twist angle of different frames versus flapping frequency; (a) without membrane and (b) with membrane

### 3.7 Wing Tip Twist Speed versus Flapping Frequency

Figure 14 shows the wing tip twist speed for the three wing frames (without and with membranes) in comparison to an actual dragonfly wing. The wing tip twist speed was measured using the Vision Research Phantom Camera Control Software associated with our high frame rate camera. Vogel<sup>31</sup> stated that the wing tip twist speed varies according to size and must exceed a ratio with flight speed (wing tip twist speed: flight speed) by 3.7 or more to enable forward flight. Figure 14 shows that the PLA and acrylic wing frames (both without and with membranes) show a similar curvature trend with the actual dragonfly wing. The wing tip twist speed of an actual dragonfly wing at 30 Hz is 9.2 revolutions per second. At 30 Hz, the PLA wing shows a percentage increase of 33.3% (without membrane) and percentage reduction of 52.2% (with membrane) in comparison with the dragonfly wing. The acrylic wing shows a percentage increase of 30.4% (without membrane) and 44.4% (with membrane). The ABS wing shows a percentage reduction of 67.4% (without membrane) and 64.1% (with membrane). At 120 Hz, all of the fabricated wing frames without the membrane attached, show a slight percentage increase in comparison to an actual dragonfly wing. The ABS, PLA, and acrylic wings show a percentage increase of 6.4%, 4% and 5%, respectively. While the ABS, PLA and acrylic wing frames without membrane have a percentage of 37.5%, 35.14% and 37.4%, respectively. The ABS wing frame shows a much different curvature trend



than the others, both with and without membrane. Figure 14 shows that the wing tip twist speed is highly dependent on the flapping frequency and is less influenced by changes in the frame's flexibility. This can be confirmed by observing the curves of the wing frames with membrane. The observed trend is the same across varying flapping frequencies (10-250 Hz) for both types of wing frames.



**Fig. 14** Wing tip twist speed of different frames versus flapping frequency; (a) without membrane and (b) with membrane

Combes and Daniel<sup>32</sup> conducted a finite element analysis study on the wing structures of several different insects (including dragonflies). In all of the species that they tested, spanwise flexure stiffness

was one to two orders of magnitude larger than chordwise flexure stiffness. They concluded that stiff leading edge veins played a primary role in generating this anisotropy. Also as previously mentioned, the study conducted by Yang et al.<sup>12</sup>, concluded that spanwise flexible deformation should be limited to a small range (by use of stiff leading edges) in order to achieve higher aerodynamic performance for a flapping MAV. Alternatively, a larger chordwise deformation could serve to enhance the aerodynamic performance (e.g. lift and thrust generation).

The results of our experiments in flapping an actual dragonfly wing support this observation, by showing that chordwise deformation is very significant (Figures 10-13) compared to the spanwise deformation. These results suggest that BMAV wings should be designed with a stiff leading edge to limit the spanwise deformation and flexible ribs to keep chordwise deformation within a significant but suitable range. This indicates that the ABS wing design is better suited for use in a BMAV than the PLA and acrylic wing designs.

#### 4.0 Conclusion

One challenge in constructing a working BMAV, involves the need to fabricate a highly deformable and flexible wing that has a large load bearing capacity. An experimental study was conducted to assess elastic properties of flapping wings fabricated from three different materials (ABS, PLA, and acrylic). The structural design of each of these wings is identical and based on biomimicry of an actual dragonfly wing. The experimental results were compared to the actual dragonfly wing, on which they are based, in order to assess their potential application to a BMAV design. A flapping mechanism that uses an electromagnetic actuator is used. This mechanism was used to flap the wings at various frequencies from 10 to 250 Hz. A high frame rate imaging system, that uses two cameras, was used to capture the three dimensional motion of the flapping wing. Several different elastic parameters were measured: bending angle, wing tip deflection, wing tip twisting angle, and wing tip twisting speed. Analysis of wing bending angle and wing tip deflection indicates flexibility of the wing in the chordwise direction, while the wing tip twist angle and speed shows the flexibility of the wing in the spanwise direction. The ABS wing exhibited the highest chordwise flexibility (indicated by their large bending angles and wing tip deflections). Although

the PLA and acrylic fabricated wings exhibited a much lower chordwise flexibility than the ABS fabricated wing and the dragonfly wing, their spanwise flexibility (indicated by their wing tip twist angles and speeds) closely matched the dragonfly wing.

These experimental results show that an actual dragonfly wing has a highly deformable structure despite its rigidity. The materials examined in this study (ABS, PLA and acrylic) were selected due to their high flexibility, low density, and low fabrication costs. This study shows that each of these materials is able to perform like an actual dragonfly wing to varying degrees. However, the ABS wing design gave better results in matching the chordwise flexibility of the actual dragonfly wing, while limiting the spanwise flexibility to much greater degree than the other two designs.

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Dr. Praveena Nair Sivasankaran obtained her PhD in engineering from University of Malaya. Her research focused on bio-mimicking a dragonfly wing structure. During her candidature, she published several research articles in journals that were widely cited by the scientific community. Dr. Praveena works together with her principle investigator Dr. Thomas A. Ward in developing a Biomimetic Micro Air Vehicle based on a dragonfly.

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